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HEAT PUMP DEHUMIDIFIER EFFICIENCY IMPROVEMENT EVALUATION

Report # 90-90-K

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ABSTRACT

Two heat pump dryer design changes were evaluated in the Process Applications Laboratory: (1) re-direction of air flow to allow "open-cycle" air flow heat recovery operation, and (2) water circulation in the "evaporator economizer" to reduce evaporator load. In addition, the reduced power consumption of a variable speed drive (VSD) was confirmed during testing. Open-cycle air flow heat recovery improved drying efficiency over the original dehumidifier by 55% during winter testing conditions, and by an estimated 38% during summer operating conditions. The evaporator economizer increases dehumidifier drying efficiency by about 9%, and allows drying at a higher temperature. A 16% reduction of air flow produces 40% reduction in electrical consumption.

Given at least 465 quality lumber dry kilns in Ontario, of which 99 employ dehumidifiers, total potential electrical reduction is estimated to be over 3 MW, or close to 17,000,000 kWh annually. The above methods of energy conservation should be investigated by cooperating with dry kiln owners and equipment manufacturers.

job	file	date	report no.
12-199	814.35	May 22, 1990	90-90-K

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HEAT PUMP DEHUMIDIFIER EFFICIENCY IMPROVEMENT EVALUATION

Richard Solczyk and Andrew Chow

1.0 INTRODUCTION

Heat pump dehumidifiers are used widely in the quality lumber industry, while other industries employ them to varying degrees. The best use of heat pump dehumidifiers in drying is when the temperature and humidity of the drying conditions are in the optimum range of the dehumidifier. Commonly available heat pump dehumidifiers operate most efficiently at:

- relative humidity above 30%, and
- dry-bulb temperature below 75°C (167°F).

The above operating conditions allow the adoption of heat pump dehumidifiers for industrial product drying in many applications, such as in the drying of quality lumber, ceramic greenware, and finished paper products. Extending the heat pump's optimum range to include relative humidity below 30% and dry-bulb temperature above 75°C can significantly improve drying performance and electrical efficiency.

Low humidity and high temperature allow more effective drying when the product is at low moisture content levels. More effective drying means shorter drying and operating times. This means lower electrical consumption by the dehumidifier and by other equipment, such as the circulation fans. Other improvement possibilities include using variable speed fans for air circulation. An increasing number of dry kilns in the United States is installing variable speed drives to existing circulation fan motors. Independent studies conducted in Oregon and in North Carolina concluded that variable speed drives can significantly reduce dry kiln electrical consumption, due to the lumber drying rate's

lower dependency on air velocity when the moisture content falls below 30%.[1] Theoretically, a 14% reduction in air flow can reduce electrical consumption by 40%.

The objective of this project is to improve the drying efficiency of heat pump dehumidifiers especially at relative humidity below 30%, and to increase the operating range to dry-bulb temperatures above 75°C. Successful improvement in this respect can reduce electrical consumption of existing dehumidifiers and improve process efficiency in the drying operation. In addition, electrical consumption of a variable speed fan is monitored to measure the potential electrical reduction at reduced operating speed.

2.0 HEAT PUMP DEHUMIDIFIER DESIGN AND CHANGES

Three changes have been incorporated into a 2-kW dehumidifier in the Process Applications Laboratory. The performance of the dehumidifier, before and after the modifications, was measured to determine any effects in drying efficiency and the associated payback periods. This report summarizes the findings of these tests. The details of the testing procedures and the theory of the design changes are included in the Appendix.

The first method to improve dehumidifier efficiency is "open-cycle" air flow which allows kiln air to be exchanged with the fresh air from outside of the kiln. The "open-cycle" refers to the air flow path, and not the refrigerant circuit. Kiln air that has been cooled and dehumidified by the heat pump's evaporator is exhausted to the outside. This reduces the temperature and the enthalpy of the exhausted air to a level comparable to that of the make-up air. The make-up air is mixed with the circulating kiln air, and then heated by the condenser before returning to the dry kiln.

The second modification is the addition of an "evaporator economizer", which allows the heat pump to operate as if the kiln is at a lower temperature and higher humidity. The evaporator economizer consists of a pump circulating water between two air-to-water heat exchangers. In the first heat exchanger, called the "hot-side" coil, the hot air entering the heat pump is cooled by the circulating water. The water is then pumped to the second heat exchanger, called the "cold-side" coil, where it heats either the refrigerated air exiting from the evaporator, or the make-up air entering the kiln. This procedure reduces the cooling load on the evaporator by reducing the temperature and increasing the relative humidity of the air entering the evaporator. Consequently, the evaporator can extract more moisture from the air.

The final modification to the dehumidifier, connecting the fan motor to a variable speed drive, allows more flexibility in varying air flow through the dehumidifier, and confirms that variable speed drives can reduce electrical consumption.

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[1] **A Guidebook to Electrical Energy Savings at Lumber Dry Kilns Through Fan Speed Reduction**, U.S. Department of Energy, Bonneville Power Administration, December 1986.

Quarterly Status Report - January - March 1989, North Carolina Alternative Energy Corporation.

3.0 RESULTS

Drying efficiency is measured by the Specific Moisture Extraction Rate (SMER), which is the ratio of the moisture extracted to the electrical consumption.

Specific Moisture Extraction Rate

$$\text{SMER} = \frac{\text{kilograms of moisture removed from the product or condensed by the heat pump}}{\text{kilowatt-hours of electrical consumption by the heat pump}}$$

The major difference between operating in the dehumidification mode and in the heat recovery mode, is the effect of outside weather conditions on the drying efficiency. By the above definition, the SMER of the heat recovery heat pump is dependent on the difference in the humidity ratio of the kiln air and the make-up air, because the moisture in the kiln air is either condensed by the heat pump or exhausted outside the kiln. At Toronto's Lester B. Pearson International Airport, the humidity ratio in the summer months is on average 0.011 kg/kg of dry air. In the winter months, it is about 0.001 kg/kg of dry air. Since the average humidity ratio in a lumber drying schedule is 0.040 kg/kg, the fluctuation in environmental humidity ratio results in the summer drying capacity being only about 75% of the winter capacity. So, the heat recovery heat pump, operating in the winter, is over 50% more efficient than the dehumidifier, while the heat pump operating in summer conditions can still be 38% more efficient than using a dehumidifier.

Figure 1, on the next page, is a summary of the Specific Moisture Extraction Rate, expressed in kg/kWh, calculated using the test result from each mode of operation. It shows that while the use of the evaporator economizer resulted in a slight improvement in drying efficiency, the heat recovery modes of operation provide significant improvement. The best drying efficiency was achieved by using the evaporator economizer in the heat recovery mode. The colder make-up air in the heat recovery test, at about 20°C, is more effective than the refrigerated kiln air in the dehumidifier test, at about 30°C, when reducing the temperature of the air entering the evaporator. This is discussed in more detail in section A.1 in the Appendix.

The evaporator economizer reduces the dry-bulb temperature of the air entering the evaporator on average from 5°C to 10°C depending on the kiln conditions. This reduction in temperature at constant humidity ratio means a corresponding increase of 5% to 20% in relative humidity. When the kiln's relative humidity is above 70%, as in the beginning of the drying cycle, the kiln air would leave the evaporator economizer at close to 100% relative humidity or saturation. This means that for very moist kiln conditions or in very cold weather, the economizer can in fact condense moisture from the kiln air.

The kiln temperature tended to rise a little more slowly during the heat recovery tests than during dehumidification tests. This reduction is due to the residual heat contained in the air exhausted to the outside and is closely related to the exhaust air flow rate. The enthalpy of the exhaust air

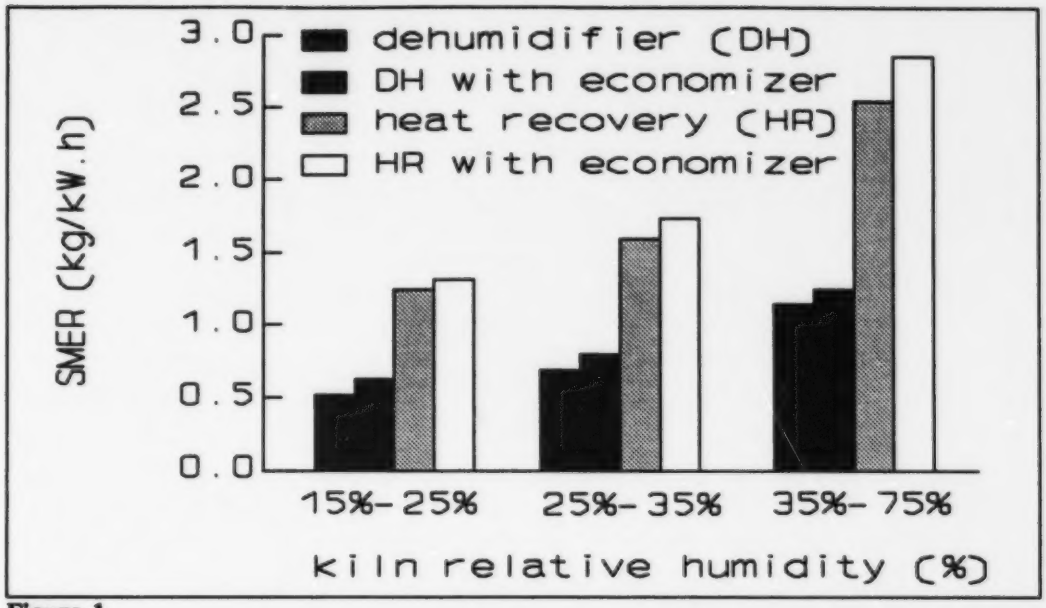

Figure 1
Summary of Specific Moisture Extraction Rates in the Four Modes of Operation

depends on its temperature, which is a function of the evaporator temperature. Lowering the evaporator temperature can reduce the enthalpy of the exhaust, and even extracting energy from outside the kiln if the enthalpy of the exhaust air is below that of the make-up air. This feature is beyond the scope of this project, but should be considered in future heat pump dryer designs.

In addition to the Specific Moisture Extraction Rate tests, the original blower motor in the heat pump cabinet was connected to a variable speed drive. This replacement was intended to allow flexibility in optimizing the air flow through the heat pump dehumidifier. The variable speed drive was tested to calibrate electrical consumption with air velocity at the blower outlet. The measurements reveal what was expected theoretically: the electrical consumption of the motor is closely proportional to the cubic power of the air velocity. This means that reducing air velocity by 16% will result in over 40% reduction in electrical consumption.

4.0 COST AND PAYBACK

Retrofitting existing dehumidifiers to allow heat recovery drying requires consideration of the circumstances of the specific dry kilns. It is not possible to predict the exact cost of the retrofit. However, the following estimation illustrates the economic feasibility of heat recovery drying.

The cost of retrofitting includes adding ductwork to the dehumidifier such that air flow can be changed from closed-cycle to open-cycle. Depending on the existing location of equipment in the dehumidifier, the retrofit can be accomplished in less than two man-weeks, with material costing about $1,000. Assuming $40.00/hour and 38 hours per week, the total cost would be about $4,000.

Installing the evaporator economizer is similar except for the additional heat exchanger related equipment, about $2,500. Since most of the evaporator economizer equipment would be installed outside of the dehumidifier, the labour cost would be correspondingly less, about one man-week or $1,500. The total cost of installing the evaporator economizer is about $4,000.

Knowing the drying efficiency and the cost of making the changes, it is possible to estimate the simple payback period of the changes. The calculations will assume a typical 30-kW heat pump operating 5000 hours annually, at an average cost of electricity of $0.06/kWh. This means annual electrical consumption of 150,000 kWh or $9,000. The simple payback period based on energy saving alone, is calculated, as shown below, by determining the cost saving and dividing it into the cost of that particular improvement. These are tabulated in **Table I**.

Simple Payback Calculation

$$SPP = \frac{COST}{OAC \times EIP}$$

where:

- SPP = simple payback period (yr)
- EIP = efficiency improvement percentage
- COST = cost of making improvement
- OAC = original annual operating cost

The second column in **Table I** is calculated from the weighted average of the SMER shown in **Figure 1** on page 4. The third column shows the estimated cost of the design changes. The last column gives the simple payback period.

Table I SUMMARY OF EFFICIENCY AND COST OF IMPROVEMENTS

method	efficiency improvement	cost	payback period
evaporator economizer	8%	$4,000	5.5 years
open-cycle heat recovery	55%	$4,000	0.8 years
combination of both	60%	$8,000	1.5 years

It is apparent from **Table I** that the addition of an evaporator economizer alone is insufficient for a satisfactory payback. However, using the evaporator economizer in combination with open-cycle heat recovery will provide a simple payback of about 1.5 year. The evaporator economizer can be designed to allow the heat pump dryer to operate at a higher dry-bulb temperature than otherwise possible. The subsequent reduction in drying time, due to the higher drying temperature, may be more important to the dry kiln operator than the payback period calculated solely on energy savings.

5.0 MARKET AND LOAD IMPACT

The lumber industry in Ontario consists of the hardwood and the softwood markets. The annual production in the hardwood market has a total volume of about 500,000 cubic metres or 210,000 Mfbm. [2] Most of this is quality maple, oak, birch, and other hardwood for the furniture and manufacturing industry. The softwood market has a total volume of about 3,600,000 cubic metres or 1,530,000 Mbfm. Most softwood lumber is construction grade spruce-fir-pine, which is usually dried four times faster than hardwood. However, some high quality pine lumber is dried at conditions similar to those for hardwood.

A survey of Ontario quality lumber dry kilns[3], carried out by Jellicoe Resource Associates Ltd. and commissioned by Ontario Hydro's Industrial Program Department, shows that there are 99 dehumidifier dry kilns out of a total of 465. Dehumidification kilns represent a total capacity of 3,150 Mbfm out of a combined total of 16,250 Mbfm for all kilns. For these dry kilns, electrical load is estimated to be 1,500 kW of dehumidifiers, and 10,000 kW of circulation fans. The following calculations assume that 100% of existing dehumidifiers would retrofit to simple open-cycle heat recovery operation, reducing electrical consumption by 25%, and that 100% of all dry kilns would install variable speed drives for the circulation fan motors, reducing electrical consumption by 30%.

dehumidifier load reduction: 1,500 kW x 25% = 375 kW
circulation fan load reduction: 10,000 kW x 30% = 3,000 kW

Furthermore, assuming 5000 operating hours per year, the annual electrical energy consumption reduction can be estimated:

dehumidifier load reduction: 375 kW x 5,000 h = 1,875,000 kWh
circulation fan load reduction: 3,000 kW x 5,000 h = 15,000,000 kWh

Table II - Summary of Potential Load Reduction for the Quality Lumber Market

Method	Affected Load	Reduction		
		percentage	load	consumption
Heat Recovery	1,500 kW	25%	375 kW	1,875,000 kWh
Variable Speed Fans	10,000 kW	30%	3,000 kW	15,000,000 kWh
Total	11,500 kW		3,375 kW	16,875,000 kWh

[2] Mfbm stands for a thousand board feet, which is a measure of lumber volume. A board foot is defined as a volume 12 inches by 12 inches by one inch thick.

[3] Quality lumber is dried at lower temperature and higher humidity to a lower final moisture content, requiring a longer drying time, than construction grade lumber. Most quality lumber is dried at temperatures below 75°C (160°F) from about 60% moisture contents to below 10% requiring more than 10 days. Most construction grade lumber is dried at temperatures above 75°C (160°F) from moisture contents over 60% to about 19% requiring less than 4 days.

Table II is a summary of the potential load reduction in the quality lumber market. Similar analysis is possible for the construction-grade lumber market, but requires a similar survey of existing construction-grade lumber dry kilns in Ontario.

6.0 CONCLUSIONS

Test results indicate that up to 50% of reduction in electrical consumption is possible when a dehumidifier is modified to operate as a heat recovery heat pump. This project and an appropriate field-trial demonstration may convince dehumidifier manufacturers, and industrial dehumidifier owners to employ the more efficient technology.

Although the evaporator economizer requires a relatively long payback period, it allows a higher kiln temperature to be used. The subsequent reduction in drying time may be more important to the kiln operator than the payback period calculated using only energy considerations.

The power consumption for the variable speed fan motor was found to be proportional to the cubic power of the air speed. Since the drying process does not require high air flow velocity throughout the drying cycle, it is possible to further reduce electrical consumption by reducing the air velocity as the cycle progresses. This consideration should be pursued in future related projects.

The potential electrical reduction due to variable speed fans and heat recovery drying is estimated to be over 3 MW, or close to 17,000,000 kWh annually.

7.0 RECOMMENDATIONS

The following schedule is a possible timetable for taking the necessary steps in helping the lumber industry adopt energy efficient drying technology:

(1) contact manufacturing and trade allies for reviewing this report, and establishing potential co-operative ventures,
(2) conduct survey of softwood dry kilns in Ontario,
(3) identify and characterize new opportunities in heat recovery drying of softwood, and opportunities for reducing electrical consumption by using variable speed fans,
(4) identify kilns currently using electric resistive heaters either to assist warming up the lumber or to dry at temperatures higher than 75°C, (heat recovery drying allows reduction in electric demand by reducing resistive heater load),
(5) monitor and document actual savings when using variable speed drives, and heat recovery drying, in fossil-fuel and dehumidifier kiln drying of both softwood and hardwood,
(6) present and publish results at appropriate trade conferences and in trade journals to increase energy awareness of kiln operators.

Initial contact with manufacturers has been established, as well as with leading lumber experts in Canada. There are a few potential sites for monitoring the efficiency of variable speed drives and of heat recovery drying. A project can monitor a combination of both technologies.

8.0 ACKNOWLEDGEMENT

The support and guidance of Mr. Mike Sanio (Industrial Technologies and Products) and Mr. Carl Keyes (Utilization Section) is gratefully acknowledged.

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APPENDIX

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A.1.0 Heat Pump Dehumidifier Design and Changes

All heat pump dehumidifiers have the following basic components in the refrigerant circuit: (1) the evaporator, (2) the condenser, (3) the compressor, and (4) the expansion device. Although the direction of air flow and refrigerant flow in the circuit are fixed, these components can be physically arranged in many ways. The following paragraph will briefly review the heat pump illustrated in **Figure 2**, showing the arrangement in the heat pump dehumidifier in the Process Applications Laboratory.

The names of the components in the refrigerant circuit refer to the action on the refrigerant in that particular part of the refrigerant cycle. The compressor, as the name implies, compresses the refrigerant gas (from about 0.5 MPa to about 2.5 MPa), raising its temperature (from about 25°C to about 110°C). The next stop in the refrigerant circuit is the condenser. It is an air-to-refrigerant heat exchanger where heat is transferred from the hot refrigerant gas to the relatively cool air. The refrigerant condenses in the process (cooling to about 70°C), with the liquid going next to the expansion device. This device produces a regulated pressure drop that allows between 20% to 40% of the liquid refrigerant to vaporize, thus lowering its temperature to about 25°C. The remaining liquid is evaporated in the evaporator, which is another air-to-refrigerant heat exchanger. Heat is transferred from the hot moist kiln air to the cooler refrigerant. As the temperature of the air decreases below its dew point, moisture condenses and is extracted from the air. The evaporator is essentially the main working component of the heat pump dehumidifier. The vaporized refrigerant is then returned to the compressor for the next cycle.

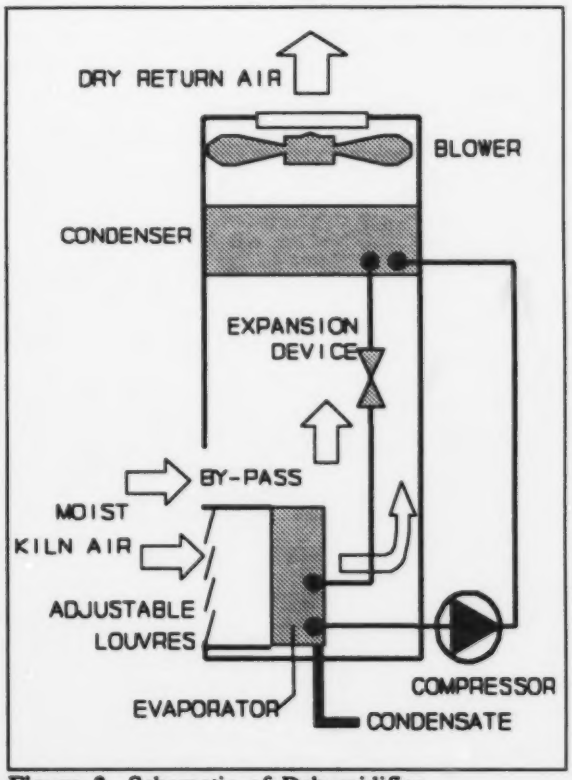

Figure 2 Schematic of Dehumidifier

The above basic description applies to all heat pump dehumidifiers. Other features depend on the manufacturer of the equipment. For example, the 2-kW dehumidifier in the Process Applications Laboratory has an the adjustable louvre in front of the kiln air inlet to the evaporator. The louvre is automatically controlled to limit the load on the dehumidifier when the kiln condition becomes too hot or too humid. Its function is to maintain a constant temperature at the compressor suction.

A.1.1 Changes to the Dehumidifier

The laboratory dehumidifier was cut in half, separating the condenser and the evaporator. The cold-side coil, along with the inlet port, the exhaust port, the "by-pass ports", and the selection baffle were inserted between the condenser and the evaporator. The selection baffle allows either the dehumidified air from the evaporator or the dry make-up air from outside the kiln to be directed first through the cold-side coil, and then to the condenser.

Two changes were tested in this project (**Figure 3**). The first change is "open-cycle" air flow which makes it possible to allow air to be exchanged with the outside of the kiln. The "open-cycle" refers to the air flow, and not the refrigerant. Kiln air is exhausted to the outside after it has been cooled and dehumidified by the evaporator. This reduces the enthalpy of the exhausted air to a level comparable to the enthalpy of the fresh make-up air which is mixed with the kiln air before being heated by the condenser. The selection baffle is either opened for dehumidification, or partially closed for open-cycle heat recovery.

The second is the addition of an "evaporator economizer" which consists of a pump circulating water between two air-to-water heat exchangers. In the first heat exchanger, the "hot-side" coil, the circulating water cools the hot air going into the evaporator. The water is then pumped to the second heat exchanger, the "cold-side" coil, where it is cooled either by the refrigerated air exiting from the evaporator or by the fresh make-up air from outside the kiln. This procedure reduces the cooling load on the evaporator, and allows more moisture extraction. The major benefit of the evaporator economizer is essentially to allow the heat pump to operate with the kiln at a higher temperature and lower humidity with the same efficiency as if the kiln is at a lower temperature and higher humidity.

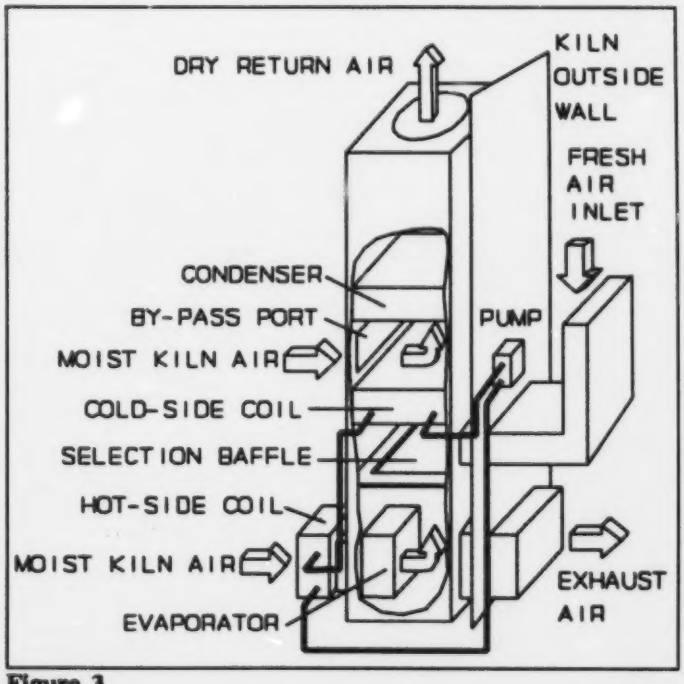

Figure 3
Cut-away Diagram Showing Changes in the Dehumidifier

In order to understand the two changes in more detail, the dehumidification efficiency of a heat pump with and without the changes is estimated in the following sections for low humidity operating conditions. For simplicity, the calculation considers only the energy and mass balance of the air flow through the evaporator and the condenser, and ignores the refrigerant and the compressor. This procedure is applied to all the calculations because the result is used for the purpose of comparing the different modes of operation. Since the calculations in the following sections do not consider the heat transfer coefficient of the heat exchangers, and the coefficient of performance of the heat pump,

it is expected that the result of the calculations would be different from that from test measurements. Nonetheless, the exercise is useful for comparing the drying efficiency of the different modes of operation.

Dehumidification efficiency is generally measured by the Specific Moisture Extraction Rate (SMER). The SMER is the ratio of the moisture removed and the energy consumed in the process. The unit of measurement is in kilograms of moisture removed per kilowatt-hour of electric consumption. It is analogous to the Coefficient of Performance (C.O.P.) used for measuring refrigeration efficiency. The reciprocal of SMER gives a measure of the specific energy requirement for removing a kilogram of moisture. As an illustration, an ideal system that perfectly evaporates one kilogram of water, consuming only the latent heat of vaporization, would require 2250 kJ or 0.625 kWh. The SMER for such a system would be the reciprocal of 0.625 or 1.60 kg/kWh. A practical drying system, without reclaiming the heat of vaporization, can operate at about 0.8 kg/kWh. Heat pump dehumidifiers, operating with C.O.P. of 2 or more, and recovering the latent heat of vaporization, can approach and even exceed the ideal SMER of 1.6 kg/kWh.

A typical lumber dry kiln is a batch dryer that operates on a schedule of temperature and humidity. The drying schedule maximizes the lumber drying rate by progressively lowering the humidity while the temperature is progressively increased. At the end of the schedule, the drying conditions become very hot and dry. Since dehumidification already operates at very high efficiency under normal drying conditions, the operating condition being considered is of the most severe drying condition normally found in a lumber dryer, when dehumidifier efficiency becomes comparable to the conventional heat-and-vent method, and requires the most improvement. So, the kiln condition illustrated below is at 15% relative humidity and 70°C. As test results show on page 22, the efficiency improvement increases the drying capacity over the entire range of temperature and relative humidity. The more severe conditions are illustrated below because higher temperature and lower relative humidity increases product drying rate and reduces other electrical equipment operating time and overall electrical consumption.

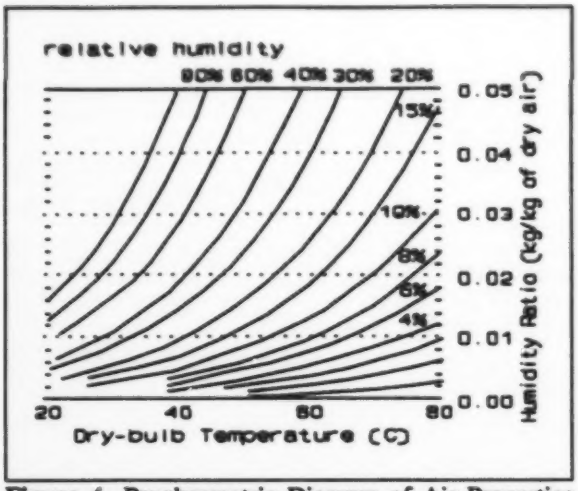

Figure 4 Psychrometric Diagram of Air Properties

Enthalpy of the Air

enthalpy = (1.805 x T + 2501) x W + T

where: T = the dry-bulb temperature in °C
W = the humidity ratio of the air
enthalpy is measured in kJ/kg of dry air

The calculations for each mode of operation are tabulated showing the properties of the air as it travels through the dehumidifier. A psychrometric chart accompanies each table to illustrate the condition of the air as it goes through the dehumidifier. The psychrometric chart is shown in **Figure 4** with the temperature on the horizontal axis (from 20°C to 80°C) and the humidity ratio (kilogram of moisture per kilogram of dry air) on the vertical axis on the right (from 0.000 kg/kg to 0.050 kg/kg). The contours of constant relative humidity are shown as upward curves. The enthalpy of the air can be calculated from the temperature and humidity ratio using the equation shown to the right of **Figure 4**.

A.1.2 Dehumidification

During dehumidification at low humidity conditions, **Figure 5** and **Table III** show how most of the dehumidifier's load, is sensible heat, which is related to the air temperature, rather than latent heat, which is related to the moisture in the air. About 50 kJ/kg out of 77 kJ/kg, or 65% of the total load cools the air towards its dew point (point B in **Figure 5**). Only one-third of the dehumidifier's capacity actually extracts moisture from the air (point B to point C). The dehumidified air from the evaporator is then mixed with kiln air to increase its heat capacity for absorbing the heat load in the condenser. The mixing ratio is about 6:1 for kiln air to dehumidified air (point C to point D). The mixed air then goes through the condenser and is returned to the drying chamber (point E), at a higher temperature and lower humidity than when it entered the dehumidifier.

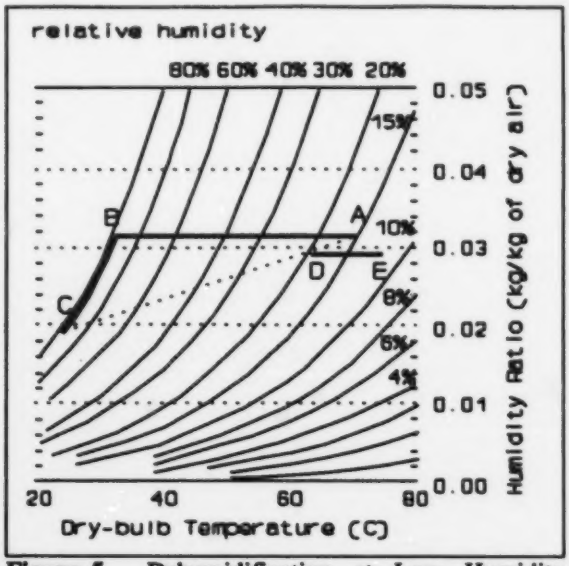

Figure 5 Dehumidification at Low Humidity Conditions

Table III
Dehumidification at Low Humidity Conditions
(Refer to Figure 5)

label	location	temperature (C)	% RH	enthalpy (kJ/kg)	humidity (kg/kg)
A	evaporator inlet	70	15	151	0.0307
B	dew point	30	100	101	0.0277
C	evaporator outlet	25	95	74	0.0194
D	condenser inlet	64	19	140	0.0290
E	condenser outlet	74	12	151	0.0290

The specific energy of extracting moisture at this kiln condition can be calculated by dividing the amount of moisture condensed, into the amount of heat absorbed by the evaporator. The amount of moisture condensed is calculated from the difference in the humidity ratio of the air before and after the evaporator. The heat absorbed by the evaporator is similarly calculated from the difference in the enthalpy of the air before and after the evaporator (point A and C).

$$\text{Specific Energy} = \frac{\text{Enthalpy}_{A-C}}{\text{Humidity}_{A-C}} = \frac{151 - 74}{0.0307 - 0.0194} = 6800 \text{ kJ/kg}$$

A.1.3 Open-Cycle Heat Recovery

In the case of the open-cycle heat recovery heat pump, **Figure 6** and **Table IV** show that the evaporator recovers heat from the exhaust air (path A-C) while the condenser heats the make-up air (path D-E), which has been mixed with the kiln air at a ratio of 6:1 (the same ratio as in dehumidification).

The make-up air is assumed, in this calculation, to be at 20°C and 60% RH (point F in **Figure 6**). This means the make-up air has a humidity ratio of 0.0087 and a dew point of 12°C. This assumption is generally valid. The effects of normal weather changes on the drying efficiency of the open-cycle heat pump can be found in section A.3.1.

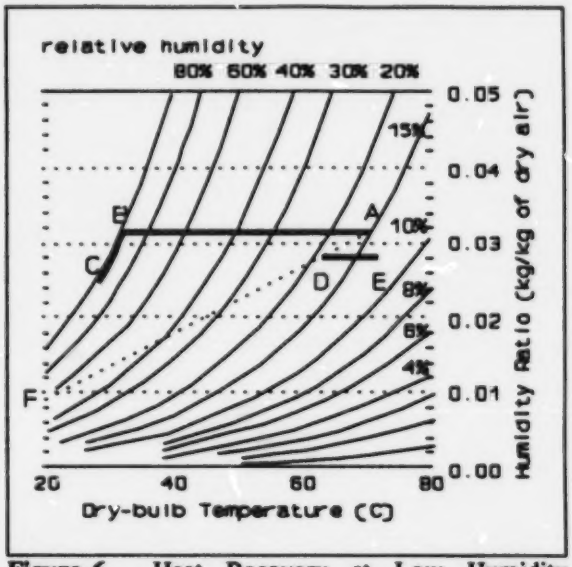

Figure 6 Heat Recovery at Low Humidity Conditions

Open-cycle heat recovery is more efficient than the dehumidifier illustrated earlier because less energy is needed to heat the make-up air to the kiln temperature than it is to cool the kiln air to the dew point of the make-up air. As seen in the following calculations using the specific energy calculated in **Figure 6** and in **Table IV**, the specific energy requirement is 62% lower for the open-cycle heat recovery method.

Table IV
Open-Cycle Heat Recovery Drying at Low Humidity Conditions
(Refer to Figure 6)

label	location	temperature (C)	% RH	enthalpy (kJ/kg)	humidity (kg/kg)
A	evaporator inlet	70	15	151	0.0307
B	dew point	30	100	101	0.0277
C	evaporator outlet	29	95	94	0.0254
D	condenser inlet	63	18	136	0.0276
E	condenser outlet	71	13	144	0.0276

$$\text{Specific Energy} = \frac{\text{Enthalpy}_{A\text{-}C}}{\text{Humidity}_{A\text{-}C}} = \frac{151 - 94}{0.0307 - 0.0090} = 2600 \text{ kJ/kg}$$

$$\text{Efficiency Improvement} = \frac{6800 - 2600}{6800} = 62\%$$

The specific energy calculated from values in **Table III** on page 14 and **Table IV** on page 15 are respectively 6800 kJ/kg and 2600 kJ/kg. Therefore, the reduction is 4200 kJ/kg or 62% of the original requirement. In **Table IV**, the air is 71°C at the condenser outlet, which is at a lower temperature and enthalpy than that in the dehumidifier. This is later verified in the test results, which show that this difference is insignificant when compared to the extra heat supplied by the compressor. This extra heat tends to increase the temperature of the kiln and often requires periodic venting to lower the temperature. The heat recovery operation is effectively a more efficient method of maintaining a slower rate of temperature increase than the conventional method of venting the kiln. Another advantage of the open-cycle heat recovery method is its capacity to extract energy from the make-up air. When the enthalpy of the air at the evaporator outlet (point C in **Figure 6**) is less than the enthalpy of the make-up air from the outside temperature (point D in **Figure 6**), the heat pump is in fact extracting energy from the outside. This can be utilized for the initial heat-up of the product at the start of the drying operation.

A.1.4 Evaporator Economizer

The purpose of the second improvement, the "evaporator economizer", is to reduce the refrigerating load by using the cold dehumidified air leaving the evaporator to cool the hot humid air entering the evaporator. This can be accomplished by using two air-to-water heat exchangers, with the "hot-side" coil and the "cold-side" coil located respectively at the inlet and the outlet of the evaporator. **Figure 7** and **Figure 8** show respectively the air flow pattern through the evaporator economizer in the dehumidifier configuration and in the open-cycle heat recovery configuration. The circulation pump is the only active component in the evaporator economizer. The electrical consumption of the pump is insignificant (1/25 horsepower or 0.03 kW), compared to that of the heat pump (2 kW). It circulates water between the hot-side and the cold-side heat exchangers. The hot-side coil at the inlet of the evaporator cools the incoming hot humid air. The cold-side coil below the condenser can be cooled either by the cold dehumidified air leaving the evaporator, or by the cool dry make-up air from the outside. Depending on the mode of operation and how the selection baffle is set, the air going into the condenser can be from either the evaporator, or from outside the kiln. In the dehumidifier mode, the selection baffle is open, while the make-up and exhaust ports are shut. In the open-cycle heat recovery mode, the selection baffle is partially closed, while the make-up and exhaust ports are open. The top by-pass port always remains open, allowing the same ratio of kiln air to be mixed with the pre-heated air.

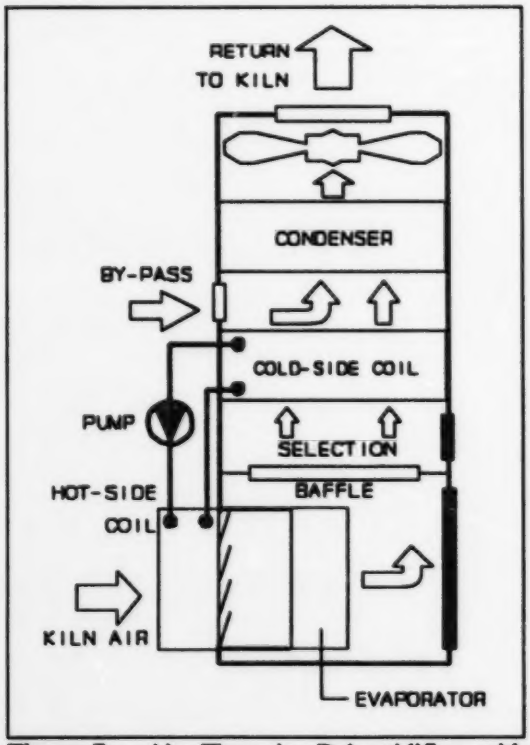

Figure 7 Air Flow in Dehumidifier with Evaporator Economizer

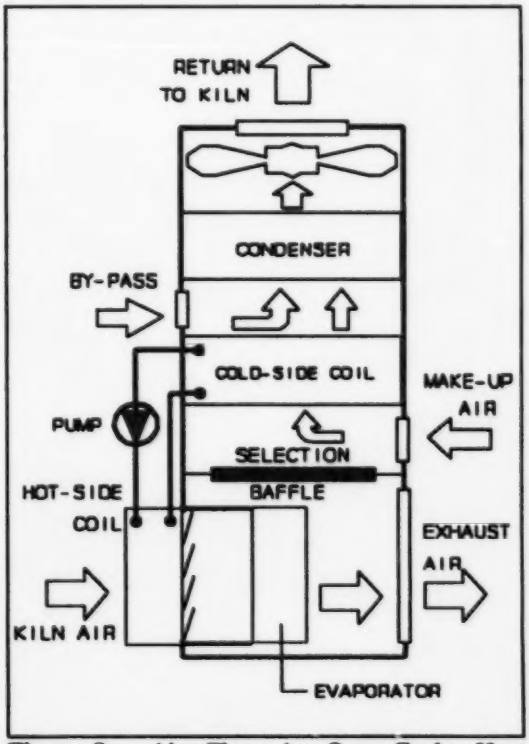

Figure 8 Air Flow in Open-Cycle Heat Recovery with Evaporator Economizer

A.1.5 Dehumidification with Evaporator Economizer

Figure 9 and **Table V** show the economizer cooling the kiln air (point A) to above the dew point temperature (point B). This allows a larger portion of the evaporator's capacity to extract moisture from the air (path C-D-E). Downstream of the evaporator, the heat picked up at the hot-side coil is dissipated at the cold-side coil. The cold-side coil raises the temperature of the dehumidified air (path F-G) before it reaches the condenser. This pre-heated air is then mixed with the kiln air (path G-H) to increase the heat capacity for absorbing the load from the condenser. The same ratio of kiln air to dehumidified air, 6:1, is used. The condenser completes the process by returning the air to the kiln at a higher temperature and lower humidity (path H-J).

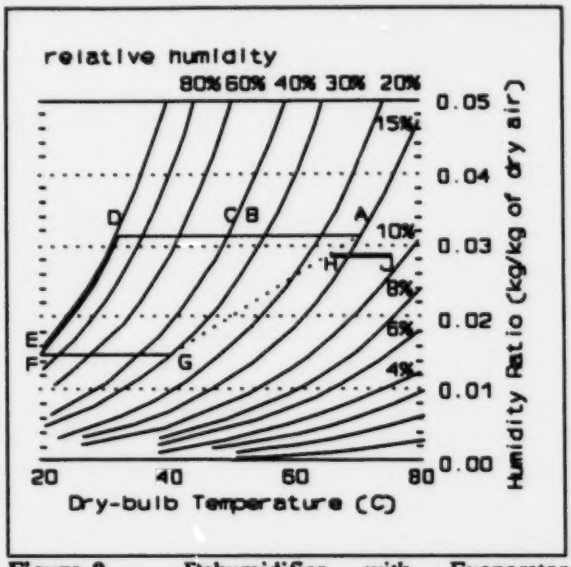

Figure 9 Dehumidifier with Evaporator Economizer at Low Humidity Conditions

Table V
Dehumidifier using an Economizer at Low Humidity Conditions
(Refer to Figure 9)

label	location	temperature (C)	% RH	enthalpy (kJ/kg)	humidity (kg/kg)
A	hot-side coil inlet	70	15	151	0.0307
B	hot-side coil outlet	50	38	131	0.0307
C	evaporator inlet	50	38	131	0.0307
D	dew point	30	100	01	0.0277
E	evaporator outlet	20	95	56	0.0142
F	cold-side coil inlet	20	95	56	0.0142
G	cold-side coil outlet	40	30	76	0.0142
H	condenser inlet	66	17	140	0.0283
J	condenser outlet	76	11	151	0.0283

$$\text{Specific Energy} = \frac{\text{Enthalpy}_{c\text{-}e}}{\text{Humidity}_{c\text{-}e}} = \frac{131 - 56}{0.0307 - 0.0142} = 4500 \text{ kJ/kg}$$

$$\text{Efficiency Improvement} = \frac{6800 - 4500}{6800} = 34\%$$

As seen in the specific energy calculations in **Table III** and in **Table V**, using an economizer in the dehumidifier reduces the specific energy requirement, from 6800 kJ/kg to 4500 kJ/kg, by 2300 kJ/kg or 34%. This is assuming ideal heat transfer efficiency in the two heat exchangers; practical reduction would be less than this ideal.

A.1.6 Open-Cycle Heat Recovery with Evaporator Economizer

In the open-cycle heat recovery configuration, the purpose of the evaporator is not to dehumidify the air. Its purpose is to extract useful heat for the condenser to raise the make-up air temperature. **Figure 10** and **Table VI** show how the economizer performs the initial cooling from the kiln temperature (point A) to slightly above the hot-side coil temperature (point B). As a result of the pre-cooling, a smaller refrigerating capacity is needed to cool the air from the hot-side coil temperature to slightly below the dew point (path C-D-E). The economizer delivers the recovered heat to the make-up air at the cold-side coil heat exchanger (path F-G). Kiln air is then mixed with the pre-heated make-up air at a ratio of 6:1, before going through the condenser (path G-H-J). As seen in the calculations below, the drying efficiency can be improved by 27% over heat recovery without the economizer, and by 72% over the original dehumidifier.

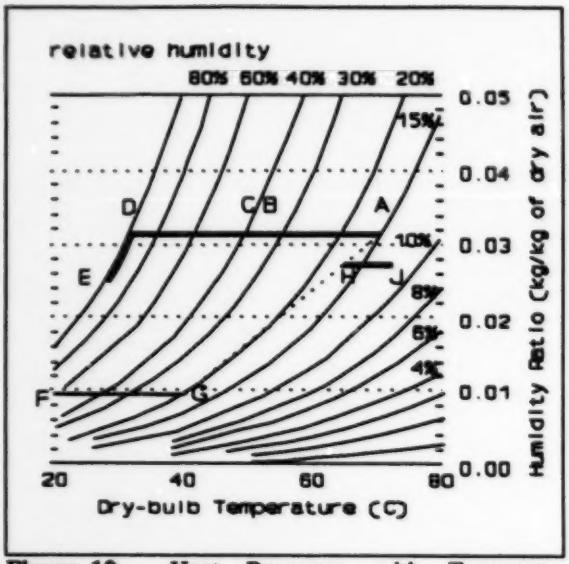

Figure 10 Heat Recovery with Evaporator Economizer at Low Humidity Conditions

Table VI
Open-Cycle Heat Recovery with an Economizer at Low Humidity Conditions
(Refer to Figure 10)

label	location	temperature (C)	% RH	enthalpy (kJ/kg)	humidity (kg/kg)
A	hot-side coil inlet	70	15	151	0.0307
B	hot-side coil outlet	50	38	131	0.0307
C	evaporator inlet	50	38	131	0.0307
D	dew point	30	100	101	0.0277
E	evaporator outlet	28	98	90	0.0244
F	cold-side coil inlet	20	60	43	0.0090
G	cold-side coil outlet	40	20	63	0.0090
H	condenser inlet	66	16	138	0.0276
J	condenser outlet	71	13	144	0.0276

$$\text{Specific Energy} = \frac{\text{Enthalpy}_{CE}}{\text{Humidity}_{CE}} = \frac{131 - 90}{0.0307 - 0.009} = 1900 \text{ kJ/kg}$$

$$\text{Efficiency Improvement over Heat Recovery without Economizer} = \frac{2800 - 1900}{2800} = 27\%$$

$$\text{Efficiency Improvement over Dehumidifier without Economizer} = \frac{6800 - 1900}{6800} = 72\%$$

Table VII is a summary of the calculated specific energy and the associated efficiency improvement. Since the calculations did not account for the heat transfer coefficient of the heat exchangers, nor the coefficient of performance of the heat pump, the calculated results are not expected to be exactly the same as test measurements. The effect of the heat transfer coefficient is to limit the amount of heat transfer possible, and the amount of temperature reduction that can be achieved. The effect of the heat pump's coefficient of performance means that the efficiency improvement is not as great as calculated. (Comparing these calculations with test measurements, section A.3 shows that the heat transfer coefficient has a greater effect on the effectiveness of the economizer than the coefficient of performance has on the efficiency of the heat recovery heat pump.)

Table VII
Summary of Calculated Drying Efficiency Improvement

method	Specific Energy kJ/kg	Improvement over dehumidifier	Improvement over heat recovery
dehumidifier	6800	-	-
dehumidifier with economizer	4500	34%	-
heat recovery	2600	62%	-
heat recovery with economizer	1900	72%	27%

A.2.0 Commissioning Procedure

After the necessary changes were made to the heat pump, it had to be re-commissioned for testing. With the water drained from the evaporator economizer and the air flow in the closed loop dehumidification mode, refrigerant was added in stages to approximately the same pressure as recommended by the manufacturer. At the same time, the refrigerant temperature and pressure at the compressor's suction and discharge were continuously monitored. The manufacturer's suggested operating conditions during maximum load (temperature = 70°C and relative humidity = 30%) are as follow:

maximum discharge temperature	= 124 °C
maximum suction temperature	= 35 °C
maximum discharge pressure	= 2.70 MPa
maximum suction pressure	= 0.48 MPa

These conditions were met by repeatedly adjusting the amount of refrigerant in the system and the amount of spring tension on the expansion valve. Refrigerant was added until the temperatures became too high. The expansion valve was then tightened to reduce the temperature until the discharge pressure became too great. This procedure was iterated until the temperature and pressure at the compressor's suction and discharge at the maximum operating condition were within the range specified above. This re-commissioned heat pump was used as a base case for comparing the effects of the new design.

A.2.1 Cost of Changes

The labour cost of installing the equipment depends on the original configuration of the heat pump. Some configurations which allow easier access to the front and back of the evaporator would induce lower labour cost than the integrated package used in the tests.

A.2.1.1 Evaporator Economizer

The cost of the evaporator economizer is mainly the cost of two heat exchangers and one circulation pump. The circulation pump installed in the dehumidifier was 1/25 hp. The test results show that a small capacity pump can be quite adequate. The pressure drop through the economizer is very small if the plumbing is designed to minimize head pressure in the expansion tank and other supplementary components. The performance of the evaporator economizer should be optimized by varying the flow rate of the water to match the flow rate of the kiln air. The results from testing the 2-kW heat pump show that the optimum flow rate was about 1.6 litres per minute. At a maximum water temperature drop of about 5°C, each kilowatt of compressor rating would require 0.3 kW (1,000 Btu/hr) of power transfer or a flow rate of 0.8 litre per minute per kilowatt of compressor rating. The total estimated cost of the heat exchanger and circulation pump is about $2,500 for a 30-kW heat pump. The cost of installation depends on the specific location of the heat pump, but is estimated to be about one man-week, or $1,500. The total cost of retrofit for installing the evaporator economizer to a 30-kW heat pump is estimated to be $4,000.

A.2.1.2 Open-Cycle Heat Recovery

The cost of re-directing the air flow to allow open-cycle heat recovery is largely due to labour when retrofitting. In manufacturing a new product, the incremental cost for open-cycle heat recovery would be less. The major component would be the cost of adding four adjustable louvres to select the mode of air flow.

The 2-kW dehumidifier used in the tests was designed to sit inside the dry kiln. This does not allow the air flow to be easily adapted for the open-cycle heat recovery configuration. The design that was selected meant major retrofit and high labour cost. A more reasonable original design would limit the retrofit to a minimum of components and labour cost. The cost of adding ductwork to a larger (30 kW) heat pump would be approximately $3,000 for labour and $1,000 for materials, for a total of $4,000.

A.3.0 Efficiency Testing

The heat pump was tested using the four different modes of operation in the following order:

1. dehumidification without the evaporator economizer
2. open-cycle heat recovery without the evaporator economizer
3. open-cycle heat recovery with the evaporator economizer
4. dehumidification with the evaporator economizer

The first mode of operation was tested again after the fourth mode of operation to verify that the heat pump did not change significantly over the duration of the tests. Test results show that the heat recovery air flow lowered the compressor's discharge temperature (by 10°C) and pressure (by 300 kPa), which increased the compressor's efficiency. Although the heat pump, operating in heat recovery mode, could theoretically be optimized further by adding more refrigerant to increase its full load capacity, no refrigerant was added to the system, nor was the expansion valve adjusted. This was done to simulate operation of the heat pump under typical conditions in the dry kiln industry. The heat pump would normally be adjusted and maintained periodically, but rarely optimized in the middle of a drying cycle. Innovative refrigerant components that adjust the refrigerant charge during a drying cycle would increase efficiency further by increasing the full-load capacity of the heat pump compressor.

A.3.1 Procedures

In each test, the temperature and humidity in the kiln were controlled through a schedule that simulates actual drying conditions. This was accomplished by spraying water onto paper towels placed on well separated trays. The trays, with the paper towels, were weighed before and after each test to determine the amount of moisture removed. In addition, the amount of moisture condensed by the heat pump was collected and measured every five minutes. The data was collected for the different modes of operation to fine tune the heat pump's operation and ultimately to determine the Specific Moisture Extraction Rate.

The amount of moisture added was on average about 8 litres for dehumidification tests and about 16 litres for open-cycle heat recovery tests. Each test lasted about 3 hours, removing all but a small

amount of the moisture. The temperature and humidity of the kiln are similar to most lumber drying schedules: starting at high humidity and low temperature (35°C, 70% RH), then gradually changing to low humidity and high temperature (65°C, 15% RH).

More than half a dozen tests were conducted for each mode of operation. It usually required thorough analysis of the data collected from the first few tests before the appropriate operating parameters could be selected to optimize performance of the new configuration. Four parameters were adjusted to optimize drying performance:

(1) evaporator air flow rate
(2) evaporator temperature
(3) economizer water flow rate
(4) bypass air flow rate

The key to optimizing performance was in finding the appropriate ratios of:

(1) air flow rate through the evaporator and through the evaporator bypass
(2) flow rate of air and of water through the economizer
(3) evaporator temperature and air dew point temperature

Since these ratios are interrelated, part of the optimization process is to select the best combination of the different parameters.

The dehumidification performance of the different operating modes is calculated from the Specific Moisture Extraction Rate, which is the ratio of total moisture extracted to the electrical consumption of the heat pump.

Specific Moisture Extraction Rate

$$SMER = \frac{\text{kilograms of moisture removed from the product or condensed by the heat pump}}{\text{kilowatt-hours of electrical consumption by the heat pump}}$$

The electrical consumption is directly measured by using power meters. The moisture removed from the kiln can be found in three ways:

(1) weighing the product before and after the tests

(2) measuring the volume of the condensate periodically

(3) measuring the difference in the humidity of the air upstream and downstream of the evaporator, and multiplied by the volume of air flow

Average Air Flow Rate

$$\text{average } AFR_w = \frac{12 \times Cd}{HR_w - HR_w}$$

where:

AFR_w = Air Flow Rate through the evaporator

Cd = Condensate collected in 5 minutes

HR_w = humidity upstream of evaporator

HR_w = humidity downstream of evaporator

All three methods were used to provide a complete picture of the heat pump's drying performance because the moisture extraction rate is the sum of two components: (1) the moisture condensed by the heat pump and (2) the moisture exhausted outside the kiln. In the dehumidification mode of operation, almost all of the moisture removed from the product would be condensed by the dehumidifier, except for a small amount that is lost due to exfiltration through leaks in the kiln. In the open-cycle heat recovery mode, about 50% of the moisture removed from the product is exhausted to the outside.

The first method, weighing before and after the test, was used to determine the total moisture removed during a test. This measurement includes: (1) the moisture that is condensed by the heat pump, (2) the moisture that is exhausted to the outside of the kiln, and (3) the moisture that is lost through exfiltration. However, the measurement cannot account for the different temperature and humidity during the drying cycle. It is an average over the entire drying cycle.

The second method, measuring the volume of the condensed moisture, is used to calculate the average air flow rate through the evaporator. By measuring the condensate collected every five minutes, it is possible to calculate the average air flow rate for that period by using the difference in humidity ratio between the air upstream and downstream of the evaporator. Since the air flow rate does not change significantly throughout the test, and is essentially constant within a period of five minutes, the average flow rate is the instantaneous air flow rate for all practical purposes.

The average air flow rate is used in the third method to calculate either the condensed moisture extraction rate (CMER) in the dehumidification mode, or the exhausted

Instantaneous Moisture Extraction Rate

condensed moisture extraction rate:

$$CMER = AFR_{da} \times (HR_{w} - HR_{da})$$

exhausted moisture extraction rate:

$$EMER = AFR_{ex} \times (HR_{ex} - HR_{ma})$$

If $AFR_{ex} = AFR_{da}$ and $HR_{ex} = HR_{da}$,
then the combined moisture extraction rate becomes:

$$TMER = AFR_{da} \times (HR_{w} - HR_{ma})$$

where:

AFR_{da} = air flow rate downstream of evaporator
AFR_{ex} = air flow rate of exhaust air

HR_{w} = humidity ratio upstream of evaporator
HR_{da} = humidity ratio downstream of evaporator
HR_{ex} = humidity ratio of exhaust air
HR_{ma} = humidity ratio of make-up air

Instantaneous Specific Moisture Extraction Rate

$$ISMER_{de} = \frac{AFR_{da} \times (HR_{w} - HR_{da}) \times H}{KWH}$$

$$ISMER_{hr} = \frac{AFR_{da} \times (HR_{w} - HR_{ma}) \times H}{KWH}$$

where:

$ISMER_{de}$ = Instantaneous SMER (for dehumidifier)
$ISMER_{hr}$ = Instantaneous SMER (for heat recovery)

HR_{w} = humidity ratio before evaporator
HR_{da} = humidity ratio after evaporator
HR_{ma} = humidity ratio of the exhaust air

KWH = kilowatt-hour consumed by the heat pump

H = time period of kilowatt-hour measurement (hours)

moisture extraction rate (EMER) in the open-cycle heat recovery mode. The instantaneous CMER is simply the air flow rate through the evaporator multiplied by the difference in humidity ratio between the air upstream and downstream of the evaporator. The instantaneous EMER is similarly calculated from the air flow rate of the exhaust multiplied by the difference in humidity ratio between the exhaust air and the make-up air. If the air flow rate through the evaporator is identical to the air flow rate of the exhaust air, then the calculation can be simplified by combining the two extraction rates into one. The total amount of moisture condensed and exhausted is simply the air flow rate multiplied by the difference in humidity ratio of the kiln air upstream of the evaporator, and the make-up air. Dividing the instantaneous MER by the instantaneous power consumed by the heat pump produces the instantaneous SMER.

The dehumidification SMER is calculated using the moisture condensed from the evaporator and the instantaneous power of the heat pump. The heat recovery SMER is calculated using the combined moisture condensed and exhausted from the kiln, and the total energy consumed. The net moisture removed from the kiln is determined by subtracting the moisture in the make-up air from the moisture in the kiln air. By definition, this SMER is dependent on the humidity ratio of the make-up air. **Figure 11** shows the average humidity ratio of the air at Toronto's Lester B. Pearson International Airport, for the years 1982 and 1983. The usual level in the summer months is 0.011 kg/kg of dry air. The usual level in the winter months is 0.001 kg/kg of dry air. Since the average humidity ratio in a lumber drying schedule is 0.040 kg/kg, the effects of fluctuating environmental humidity ratio can be significant in the two humid summer months when the drying capacity can decrease by 25%. Since the heat recovery heat pump is over 50% more efficient than the dehumidifier, it is reasonable to size the heat pump according to the summer conditions and still be significantly more efficient than using a dehumidifier.

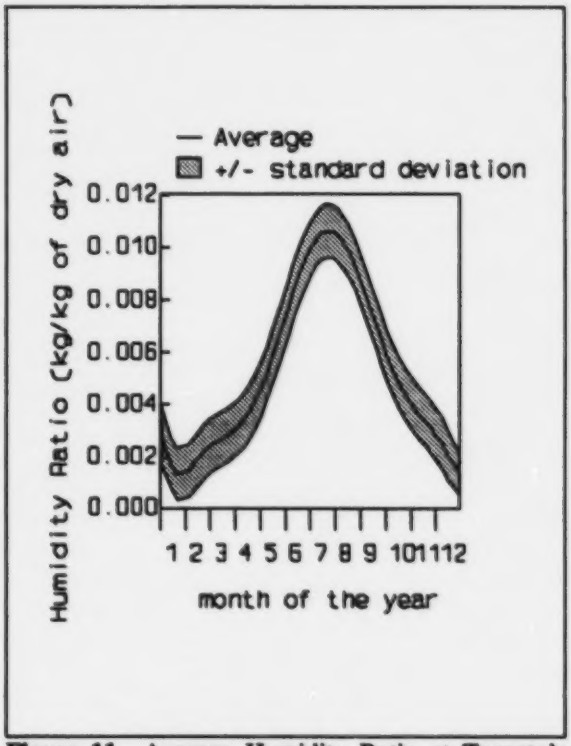

Figure 11 Average Humidity Ratio at Toronto's Lester B. Pearson International Airport (1982-1983)

A.3.2. Results

Figure 12, showing the average SMER over three ranges of relative humidity (from 75% to 35%, from 35% to 25%, and from 25% to 15%), illustrates the comparative drying efficiency of the four modes of operation. It shows that while the use of the evaporator economizer resulted in a slight improvement in drying efficiency, the heat recovery mode of operation provided significant improvement. The best drying efficiency was achieved by using the evaporator economizer in the heat recovery mode. The colder make-up air in the heat recovery test is more effective than the refrigerated kiln air in the dehumidifier test in reducing the temperature of the air entering the evaporator.

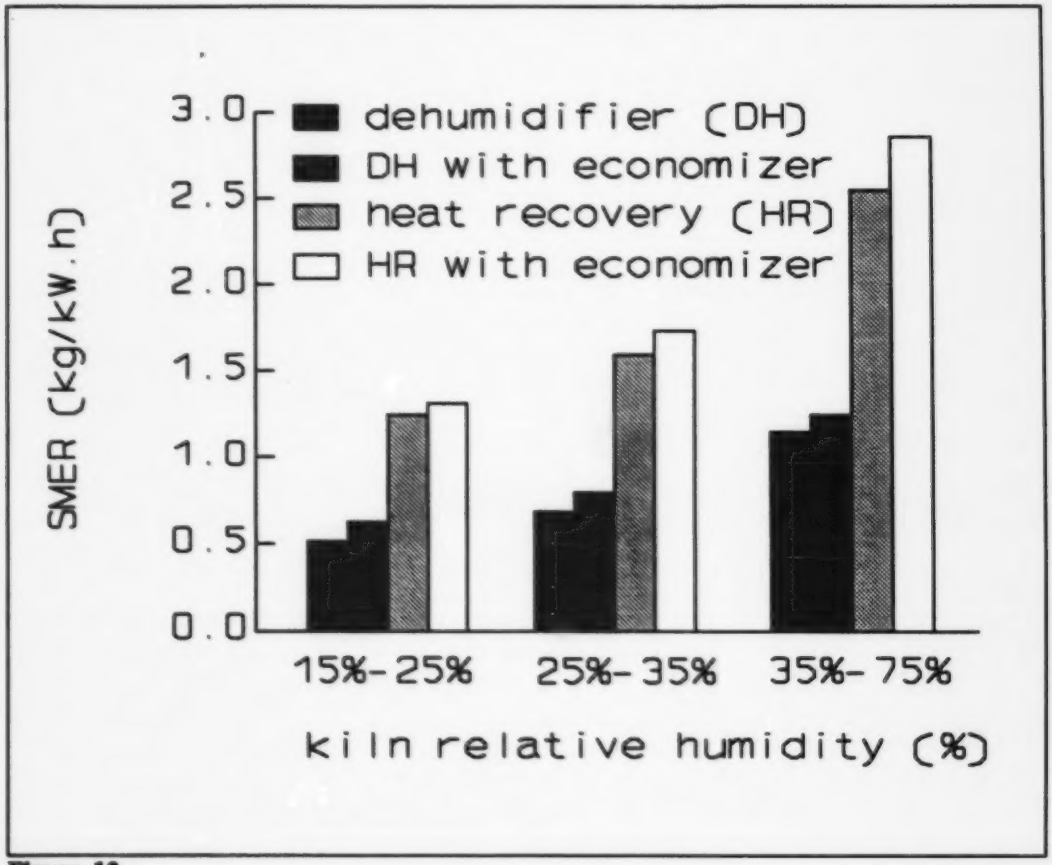

Figure 12
Summary of Average Specific Moisture Extraction Rate in the Four Modes of Operation

A.3.2.1 Evaporator Economizer

The evaporator economizer reduced the dry-bulb temperature of the air entering the evaporator on average from 5°C to 10°C, depending on the kiln conditions. This reduction in temperature at constant humidity ratio means an automatic increase of 5% to 20% in relative humidity. When the kiln's relative humidity is above 70%, as in the beginning of the drying cycle, the kiln air would leave the evaporator economizer at close to 100% relative humidity or saturation. This means that for very moist conditions, the economizer can in fact condense moisture from the kiln air. **Figure 13** and **Figure 14** show the change in temperature and relative humidity in the air entering the evaporator during both dehumidification and heat recovery tests, respectively. As would be expected, the colder make-up air in the heat recovery test tended to be more effective in the economizer, reducing the kiln air temperature more than in the dehumidifier test.

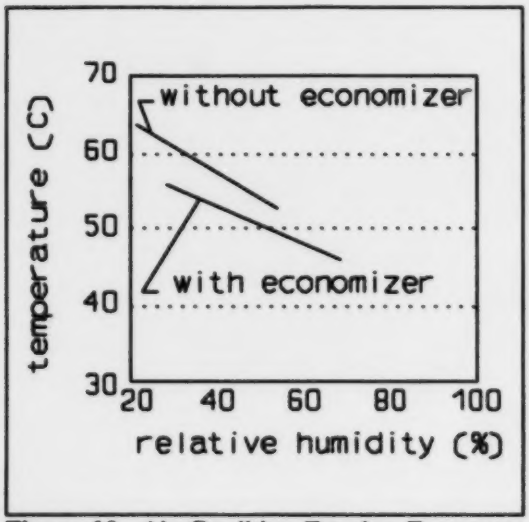

Figure 13 Air Condition Entering Evaporator in Dehumidifier

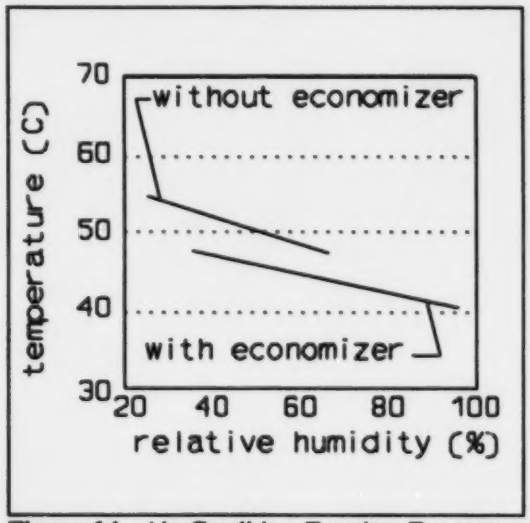

Figure 14 Air Condition Entering Evaporator in Heat Recovery Heat Pump

The tests show that the optimum performance for the economizer is when the heat capacities of the air flow and the water flow are identical. This means that the temperature drop of the air flow and the water flow are about the same. To achieve this condition, the water flow rate should be about one quarter of the air flow rate. The economizer would normally reduce the evaporator load by about 15%. This means the heat exchangers in the economizer should be sized to about 20% to 30% of the compressor rating. Test results also show that an optimized economizer is fairly stable, so that small deviations in water flow or air flow would not significantly affect performance.

A.3.2.2 Open-Cycle Heat Recovery

During the heat recovery tests, the kiln temperature tended to rise a little more slowly than during dehumidification tests. This reduction in the rate of temperature rise is due to the residual heat contained in the air exhausted to the outside and is closely related to the exhaust air flow rate. As seen in **Figure 15**, the enthalpy of the exhaust air depends on its temperature, which is a function of the evaporator temperature. The enthalpy difference between the exhaust air and the make-up air can be reduced by lowering the evaporator temperature. When the exhaust air temperature is reduced sufficiently below the make-up air temperature, energy can be extracted for heating the kiln. In general, the drier the make-up air, the greater the energy saving possible.

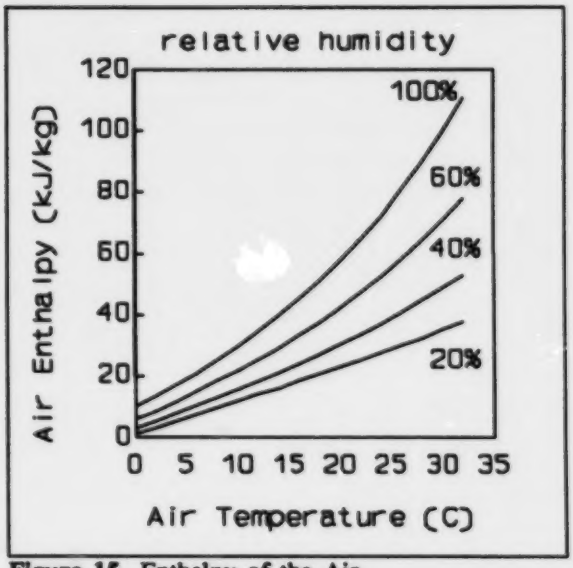

Figure 15 Enthalpy of the Air

A.4.0. Variable Air Flow

In addition to the efficiency tests, the original motor in the blower in the heat pump cabinet was replaced with a variable frequency drive motor. This replacement was intended to allow flexibility in optimizing the air flow through the heat pump dehumidifier. The variable speed motor was tested to calibrate its electrical consumption and air velocity at the blower outlet. The measurements reveal what was expected theoretically: the electrical consumption of the motor is closely proportional to the cubic power of the air velocity. This means that reducing air velocity by 16% will result in over 40% reduction in electrical consumption. Since the drying process does not require a high volume of air flow throughout the drying cycle, it is possible to further reduce electrical consumption by reducing the air velocity as the cycle progresses.

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